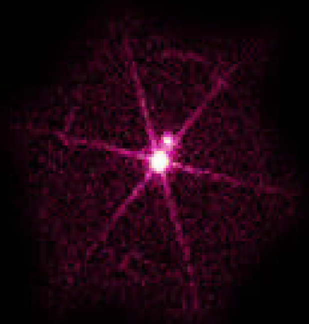
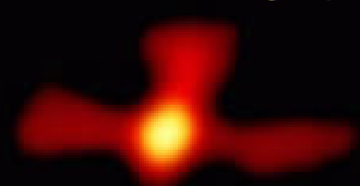
Constellation X

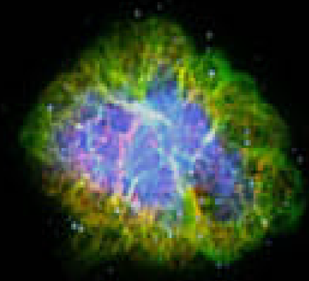
The Constellation X-ray Observatory

Recent Progress on the Constellation-X Spectroscopy X-ray Telescope (SXT)

Rob Petre (NASA / GSFC) - SXT IPT Lead
for the SXT team







SPIE
August 6, 2003

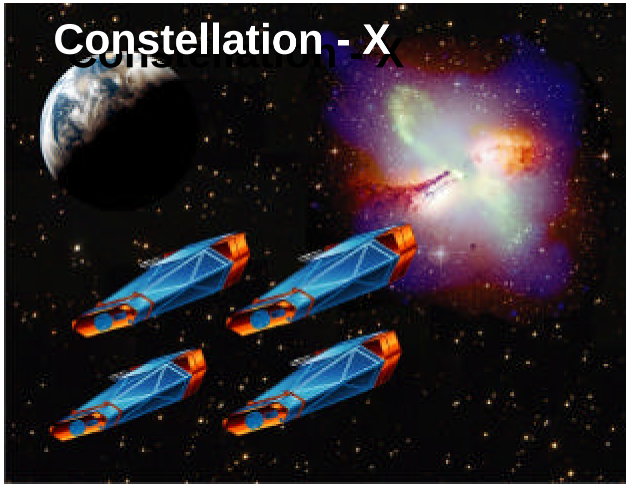
Outline of talk

- Introduction
  - Constellation-X and the SXT
  - SXT requirements and design
- Technology Development Plan Overview
- Recent Progress
  - Reflectors
  - Mandrels
  - Structure
  - Metrology
  - Testing
- Near term plans

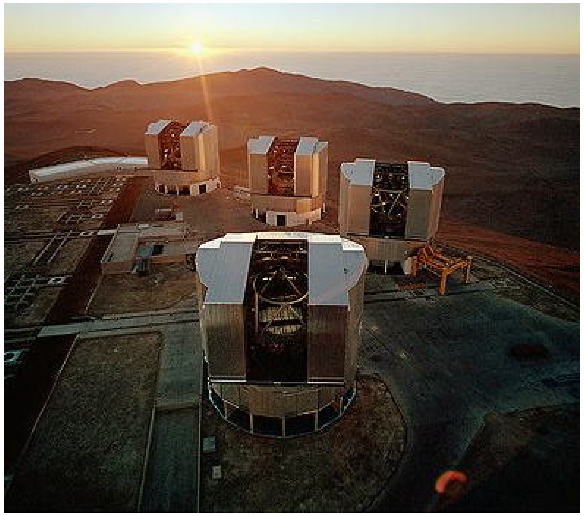
Related Papers in this Meeting

- **Forming mandrels for x-ray telescopes made of modified Zerodur,** T. Doehring et al. [5168-17]
- **Fabrication of segmented Wolter type-1 mandrels for the Constellation-X mirror development program,** W. J. Egle et al. [5168-18]
- **Development of mirror segments for the Constellation-X mission,** W. W. Zhang [5168-19]
- **Optical metrology for the segmented optics on the Constellation-X soft x-ray telescope,** D. A. Content et al. [5168-23]
- **Noncontact metrology on segmented x-ray optics for the Constellation-X SXT,** T. Hadjimichael et al. [5168-24]
- **Constellation-X SXT optical alignment Pathfinder 2: design, implementation, and alignment,** S. M. Owens et al. [5168-27]
- **X-ray testing Constellation-X optics at MSFC's 100-m facility,** S. L. O'Dell et al. [5168-34]
- **Constellation-X spectroscopy x-ray telescope image error budget and performance prediction,** W. A. Podgorski et al. [5168-35]
- **Equal-curvature x-ray telescope designs for Constellation-X mission,** T. T. Saha et al. [5168-37]

Constellation-X Mission Overview



An X-ray VLT



Use X-ray spectroscopy to observe

- Black holes: strong gravity & evolution
- Dark Matter throughout the Universe
- Production and recycling of the elements

Mission parameters

– **Telescope area:** 3 m^2 at 1 keV
25-100 times XMM/Chandra for high resolution spectroscopy

– **Spectral resolving power:** 300-3,000
3-5 times better than Astro-E2 at 6 keV

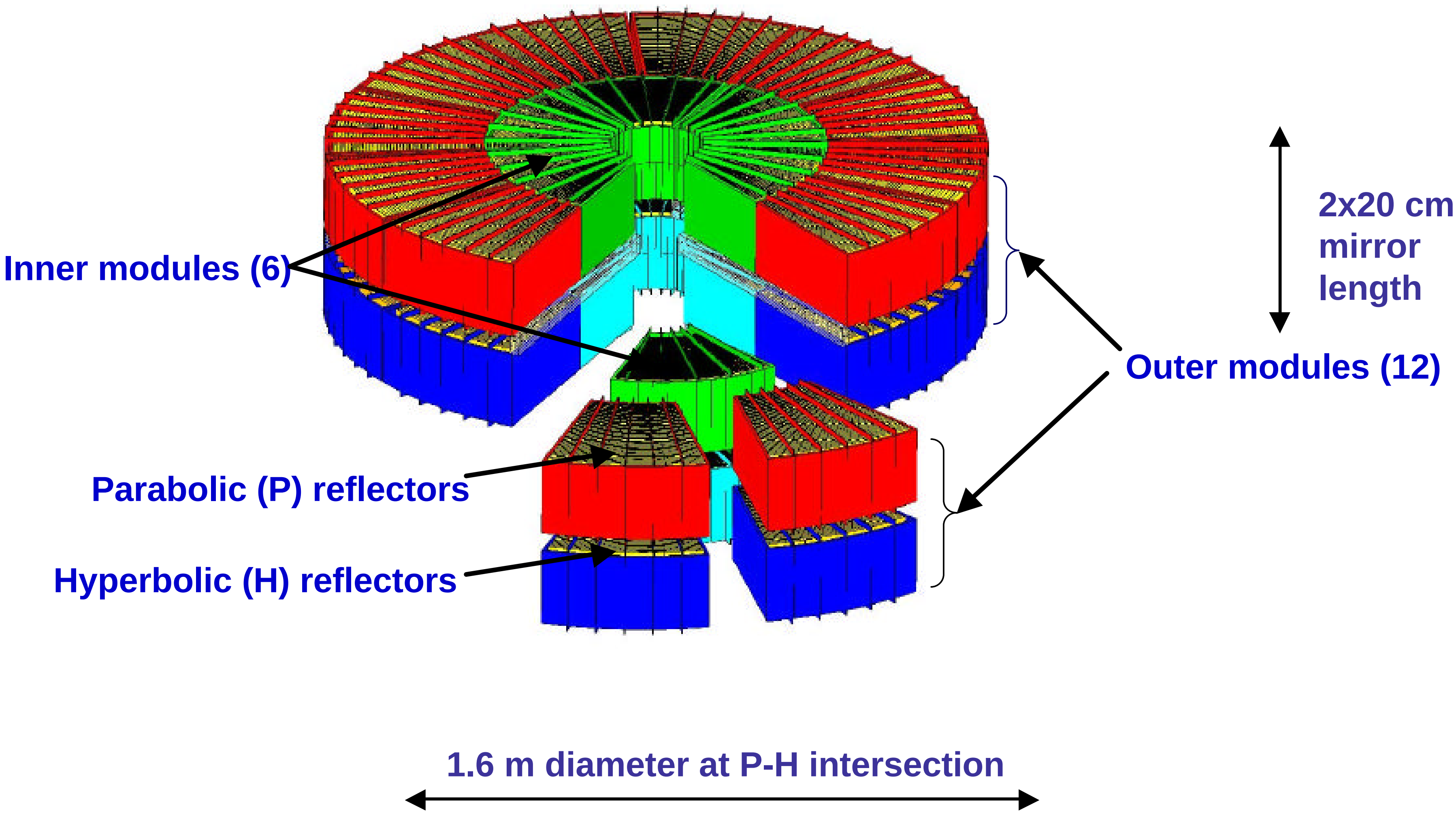
– **Band pass:** 0.25 to 60 keV
100 times RXTE sensitivity at 40 keV

Enable high resolution spectroscopy of faint X-ray source populations

SXT FMA Requirements

SXT FMA Performance Requirements		Trace to Top-Level Mission Requirements
Bandpass	0.25 to 10 keV	Allocation of mission bandpass to SXT
Effective area (per mirror) @0.25 keV @1.25 keV @6 keV	$8{,}826\ cm^2$ $8{,}421\ cm^2$ $1{,}722\ cm^2$	Provides $33{,}000\ cm^2$ at 1 keV and 6,900 cm2 at 6 keV for the mission. Allows effective area losses due to detector efficiency, etc., to achieve TLRD baseline requirement per error budget summarized in Table 1-2.
Angular resolution	12.5 arcsec HPD	Error budget allocation to mirror that allows telescope system to achieve requirement of 15 arcsec with 4 arcsec margin combined by RSS (Table 1-3).
Field of view	2.5 arcmin	Exceeds instrument FOV; defined by detector FOV
Derived Requirements: SXT Mirror		**Derivation**
Diameter	1.6 m	To meet mission area requirements with 4 mirrors
Focal length	10 m.	Consistent with grazing angle requirements for 1.6 m diameter mirror.
Axial length	<70 cm	To fit within envelope and meet fabrication considerations
Operating temperature	$20\pm1^\circ$ C nominal	Range is per allocation from SXT angular resolution error budget (Table 1-3); minimizes angular distortions imposed by temperature change to components. Operating temperature is determined by optics assembly temperature
Mass	642 kg	Current engineering estimate
Derived Requirements: Thermal Pre/Post collimators		
Temperature gradient	1° C across diameter 1° C axial	Allocation from SXT angular resolution error budget (Table 1-3); minimizes angular distortions imposed by temperature gradients
Mass	47 kg	Current engineering estimate

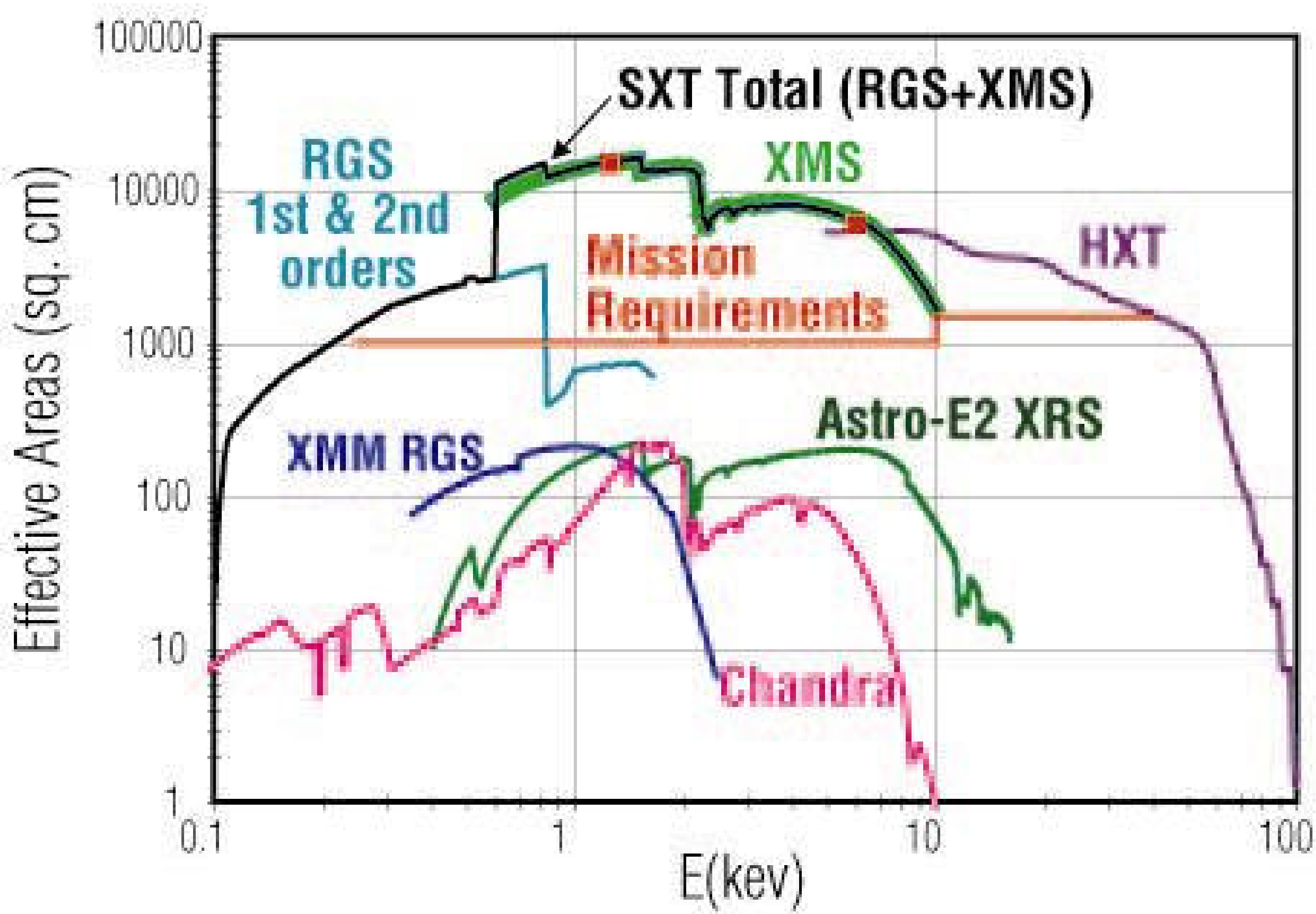
SXT Incorporates Modular Approach and Segmented Reflectors



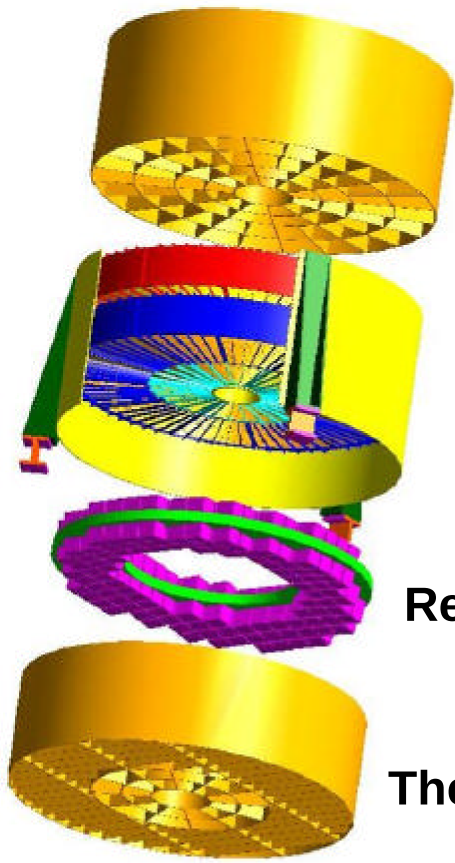
SXT Mirror Baseline Design Parameters

Parameter	Description
Design	Segmented Wolter I
Reflector substrate material	Thermally formed glass
Reflecting surface fabrication	Epoxy replication
X-ray reflecting surface	Gold
Number of nested shells	140 (inner); 90 (outer)
Total number of reflectors	3840
Reflector length	20 cm
Number of modules	6 (inner); 12 (outer)
Module housing composition	Titanium alloy, CTE-matched to substrate
Largest reflector surface area	0.16 m^2
Substrate density	2.4 gm/cm^3
Reflector thickness	0.4 mm
Reflector microroughness	0.4 nm RMS
FMA mechanical envelope	1.7 m dia x 1.65 m

SXT Effective Area



Schematic of SXT Flight Mirror Assembly (FMA)



Thermal Pre-collimator

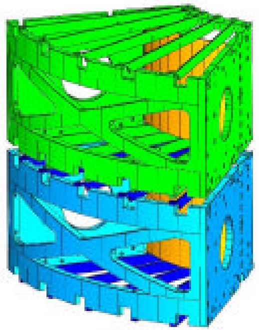
Primary and secondary optics modules

Reflection Grating Assembly

Thermal Post-collimator

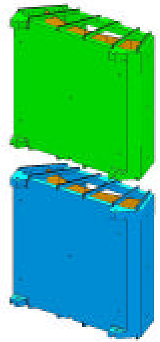
SXT Mirror Phased Technology Development

OAP 1



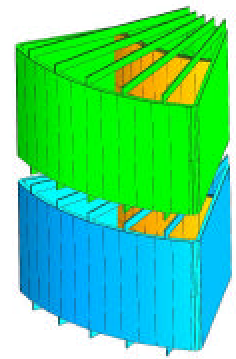
Inner Module (P&H)
Objective: Evaluate mirror assy design, alignment and metrology

OAP 2



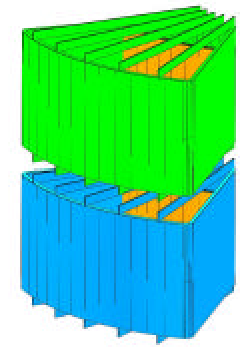
Inner Module (P&H)
Objective: Evaluate reflector, mirror bonding

EU



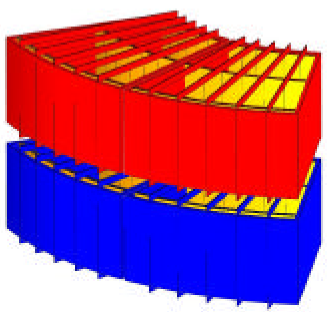
Inner Module (P&H)
Objective: Evaluate assembly gravity sag, composite housing, X-ray and environmental test

Mass Alignment Pathfinder



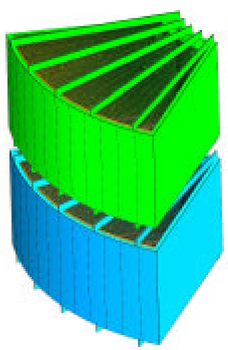
Inner Module (P&H)
Objective: Evaluate tooling and alignment techniques for mass production, X-ray test

Prototype Outer Modules



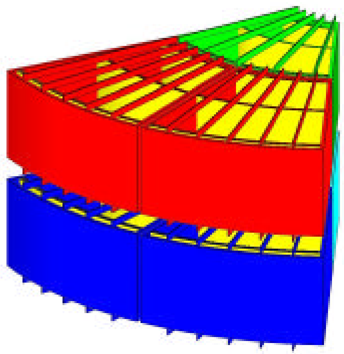
Outer modules (P&H)
Largest reflectors
Objective: Evaluate flight-like configuration outer module, X-ray and environmental test

Prototype Inner module



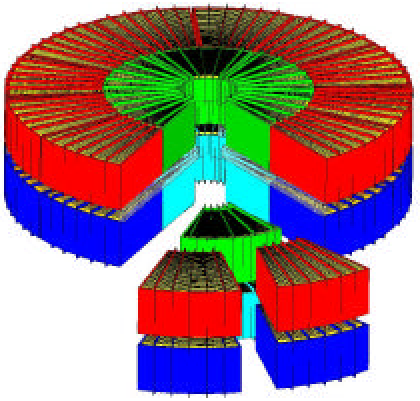
Inner module (P&H)
Objective: Evaluate flight-like configuration inner module

Prototype Wedge



Two outer modules + one Inner module (P&H)
Objective: Evaluate flight-like wedge, X-ray and environmental test

Flight Mirror Assembly (FMA)



Segmented X-ray Mirror Development Approach

	Optical Pathfinder Assembly		Engineering Unit	Mass Alignment Pathfinder	Prototype	
	OAP #1	OAP #2				
Configuration						
Module Type	Inner	Inner	Inner	Inner	Outer	Wedge (2 Outer & 1 Inner)
Housing Material	Aluminum	Titanium	Titanium/composite	Titanium/composite	Titanium/composite	Titanium/composite
Focal Length	8.4 m	8.4 m	8.4 m	8.4 m	10.0 m	10.0 m
Reflector Length (P&H)	2 x 20 cm	2 x 20 cm	2 x 20 cm	2 x 20 cm	2 x 20-30 cm	2 x 20-30 cm
Nominal Reflector Diameter(s)	50 cm	50 cm	50 cm±	50 cm±	160 cm 120 cm± 100 cm	160 cm± 120 cm± 100 cm± 40 cm±
Goals	▪ Align 1 reflector pair (P&H) ▪ Evaluate mirror assembly design, alignment and metrology	▪ Align 1 reflector pair ▪ Evaluate reflector ▪ Evaluate mirror bonding	Requirements: ▪ Align one reflector pair to achieve <12.5 arcsec ▪ X-ray test Goals: ▪ Align up to 3 reflector pairs to achieve <12.5 arcsec ▪ Characterize assembly gravity sag ▪ Environmental test ▪ Evaluate housing design	▪ Align 3 reflector pairs ▪ Evaluate tooling and alignment techniques for mass production ▪ X-ray test	▪ Flight-like configuration outer module ▪ Environmental and X-ray test ▪ Largest reflectors	▪ Demonstrate largest and smallest diameter reflectors ▪ Demonstrate module to module alignment ▪ Environmental and X-ray test
TRL	TRL 3		TRL 4		TRL 5	TRL 6
Timeframe	Q2 of FY03	Q3 of FY03	Q4 of FY04	Q2 of FY05	Q2 of FY06	Q4 of FY06
Technology Gate						

SXT - Recent Progress

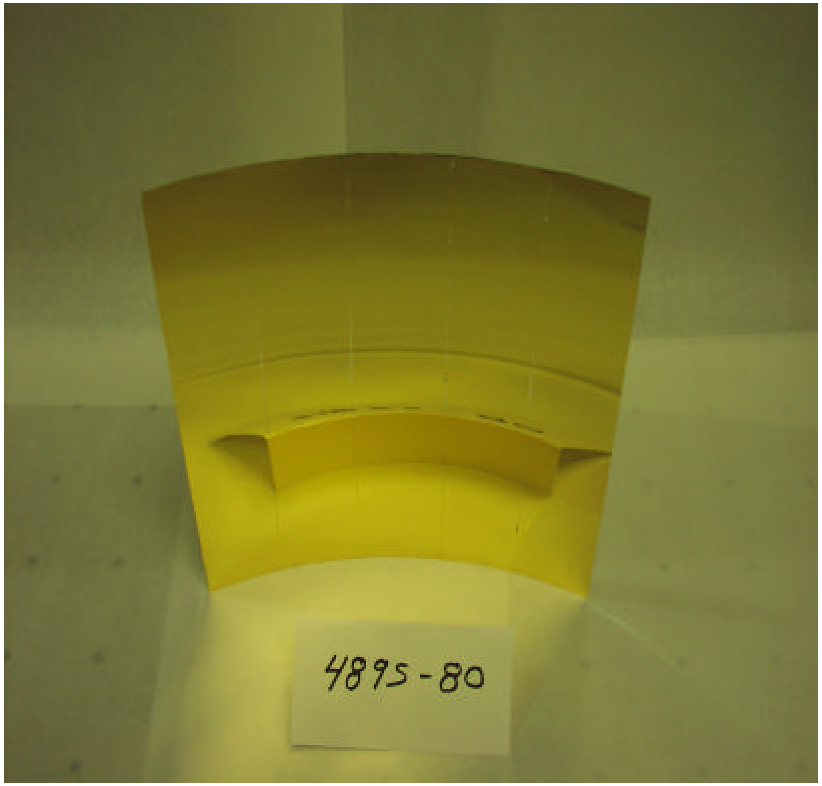
- *Constellation-X approved as part of NASA "Beyond Einstein" initiative*
  - *Working toward 2013 and 2014 launches*
- *Development has centered on 50 cm engineering testbeds with 8.4 m focal length*
  - *Utilizes available metal mandrels and preparation facilities (coating & cleaning)*
- *Substantial progress toward making 50 cm reflector segments that meet requirements*
  - *Reflector fabrication has emerged as critical path to meeting angular resolution requirement; 20 cm diameter segments consistently meet requirement*
  - *Performed replication facility rework to remove contamination (mainly dust)*
  - *Modified epoxy application approach - applied as axial strips*
  - *Reflector quality is now limited by forming mandrel quality*
- *Took delivery of 1.2 m replication mandrel from Zeiss; acceptance metrology of 1.6 m mandrel nearing completion*
- *OAP1 work completed - demonstrated ability to reproducibly manipulate and align reflectors (S. Owens talk)*
- *OAP2 work underway - learning how to bond reflectors; environmental test is pending*
- *Engineering unit housing being designed*
- *Mass alignment pathfinder concept being developed*
- *Preparations nearly complete at MSFC stray light facility for X-ray characterization*
- *Major project milestone is performance demonstration; goal is end of year*

SXT Angular Resolution Error Budget

Contributors (HPD - arcsec)	Rqmt	Margin	Allocations					Rationale
RGS Resolution	15.00	3.92	14.48					4 satellites, post-processed
▪ Co-add 4 satellites				1.00				Superposition of data using X-ray centroids
▪ On-Orbit Telescope - single satellite				14.12				RSS
▪ CCD pixelization error				0.41				0.5 arcsec pixels
▪ Grating resolution error				3.00				Estimate
XMS Resolution	15.00	4.95	14.16					4 satellites, post-processed
Co-add 4 satellites				1.00				Superposition of data using X-ray centroids
On-Orbit Telescope - single satellite				14.12				RSS
▪ Calorimeter pixelization error					4.08			5 arcsec pixels
▪ Telescope level effects					5.20			RSS
- Image reconstruction errors (over obs)						4.24		RSS
- SXT/Telescope mounting strain						2.00		Eng. estimate based on Chandra experience
- SXT/SI vibration effects						2.00		Chandra experience (jitter)
- SXT/SI misalignment (off-axis error)						1.00		Chandra experience
- SXT/SI focus error						0.20		Analysis
▪ SXT FMA - on-orbit performance					12.48			RSS
- SXT FMA launch shifts						2.00		Eng. est. based on Chandra
- Thermal errors						2.24		RSS
- Material stability effects						1.00		Est. based on Chandra work
- SXT FMA, as built						12.07		RSS
-- Gravity release							1.50	FEA analysis using vertical assy
-- Bonding strain							3.00	Eng. estimate, analysis in process
-- Alignment errors (using CDA)							3.38	RSS
-- Installation in housing							5.00	Est. based on OAP1 testing
-- Optical elements							9.90	Est. based on tech dev program

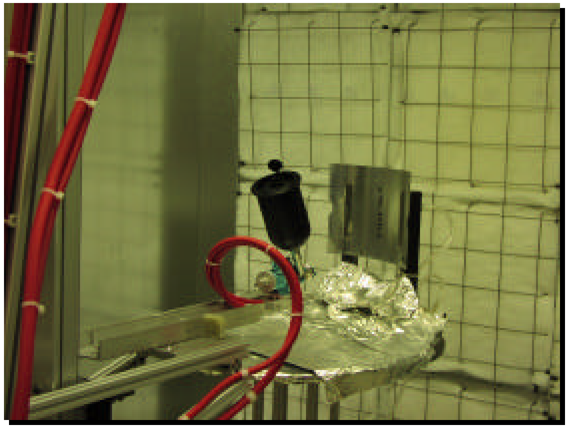
- **Achievement of 15 arc second system resolution requires <12.5 arc second SXT resolution**
- **Largest SXT error budget component is the reflector figure**

Reflector Fabrication

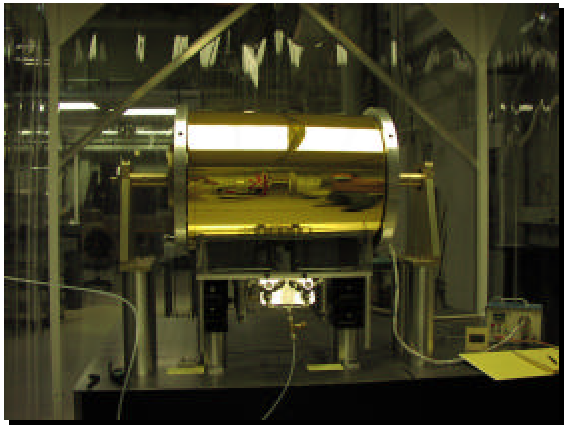


- **The reflector figure represents the largest term in the SXT angular resolution error budget**
- **The success of the SXT (and thus Con-X) depends on reflector development**
- **This is the SXT team priority**
- **50 cm development has led to numerous advances:**
  - **Development of stringent facility cleanliness requirements (removal of dust and other contaminants)**
  - **Epoxy segmentation during replication has resulted in significant stress reduction, leading to good reflector figure**
  - ***Change in overall approach to reflector development: figure must be imparted by forming mandrel; replication removes only mid-frequency terms; epoxy thickness should be minimized (with goal of zero)***

Reflector Replication

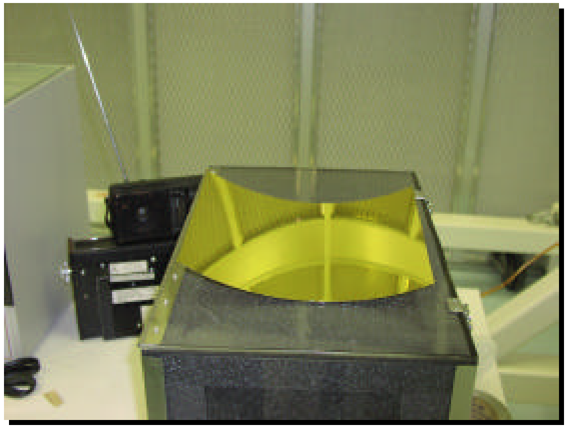


Robotic spraying of substrate



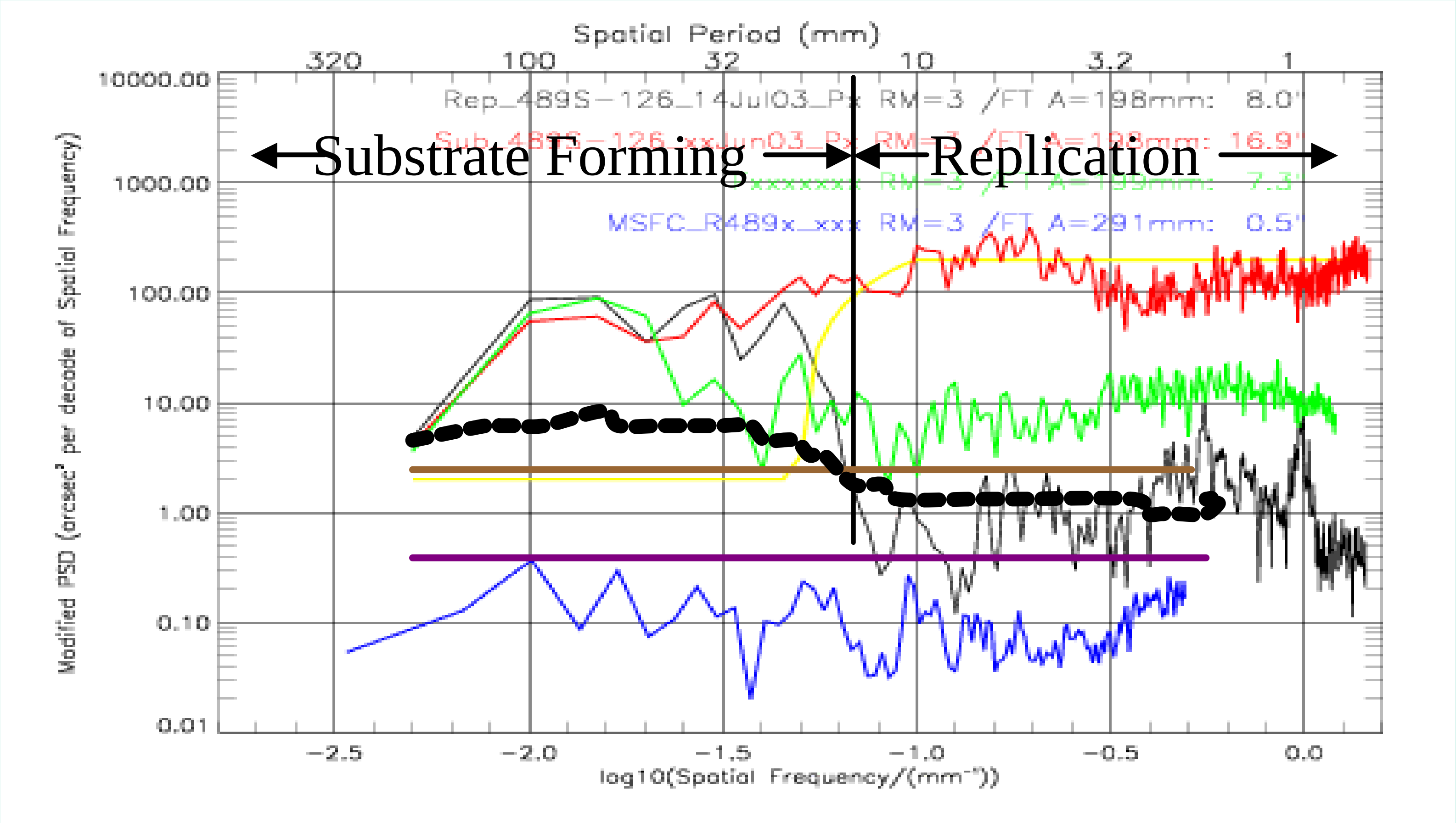
Attachment of substrate to mandrel in vacuum

Removal of finished reflector after curing



Finished reflector

A Typical Substrate and Replica



- Red: substrate;
- Black: replica;
- Green: forming mandrel;
- Blue: Zeiss replication mandrel;

•Yellow: substrate requirement;

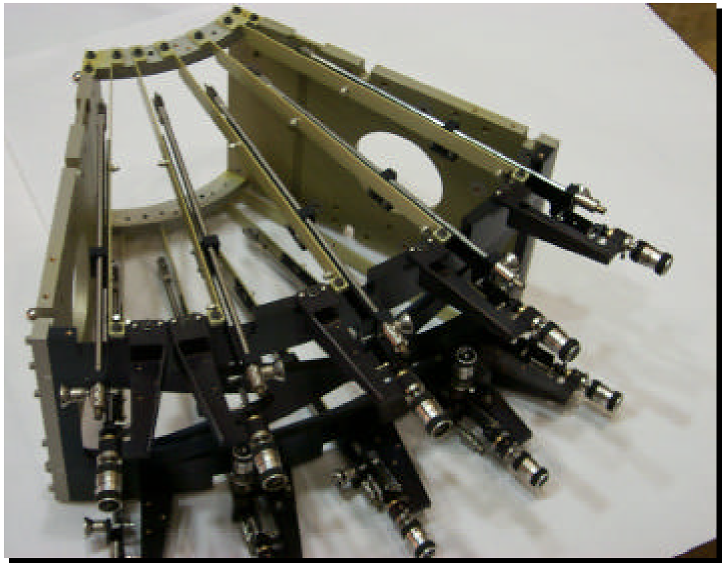
•Brown: Corresponding to a 12″ HPD (Con-X Requirement)

•Purple: Corresponding to a 5″ HPD (Con-X Goal)

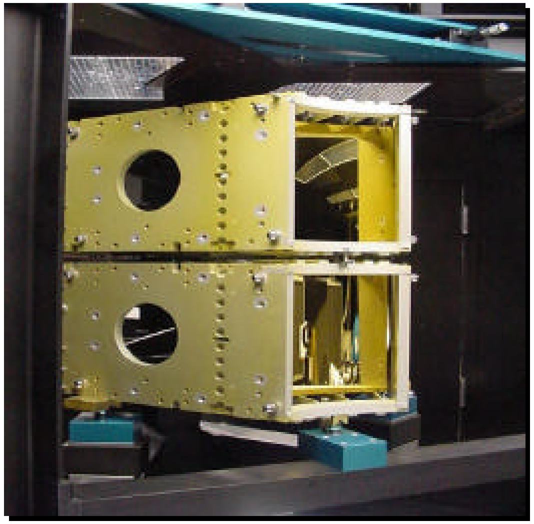
Precision forming and replication mandrels

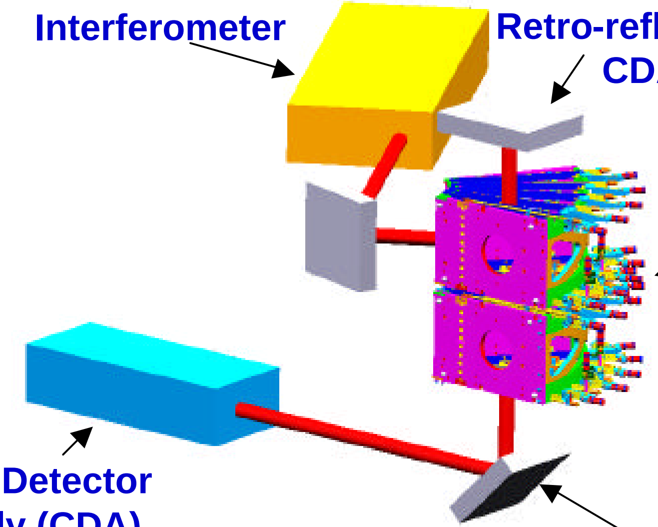
- Forming and replication mandrel production details discussed in earlier talks by T. Doehring and W. Egle
- Con-X has taken delivery from Zeiss of two precision (~4”) Zerodur replication mandrels for 30-degree arcs of 1.6 m and 1.2 m diameter mirrors; 1.0 mandrel due in ~ one month
- Schott is producing a precision Keatite forming mandrel for the 1.6 m secondary
- Figure of forming mandrels must be made more precise than previously thought as described by W. Zhang
- New 50 cm forming mandrels must be produced if OAP2 and EU are to meet resolution requirement.

OAP1 Housing and Alignment

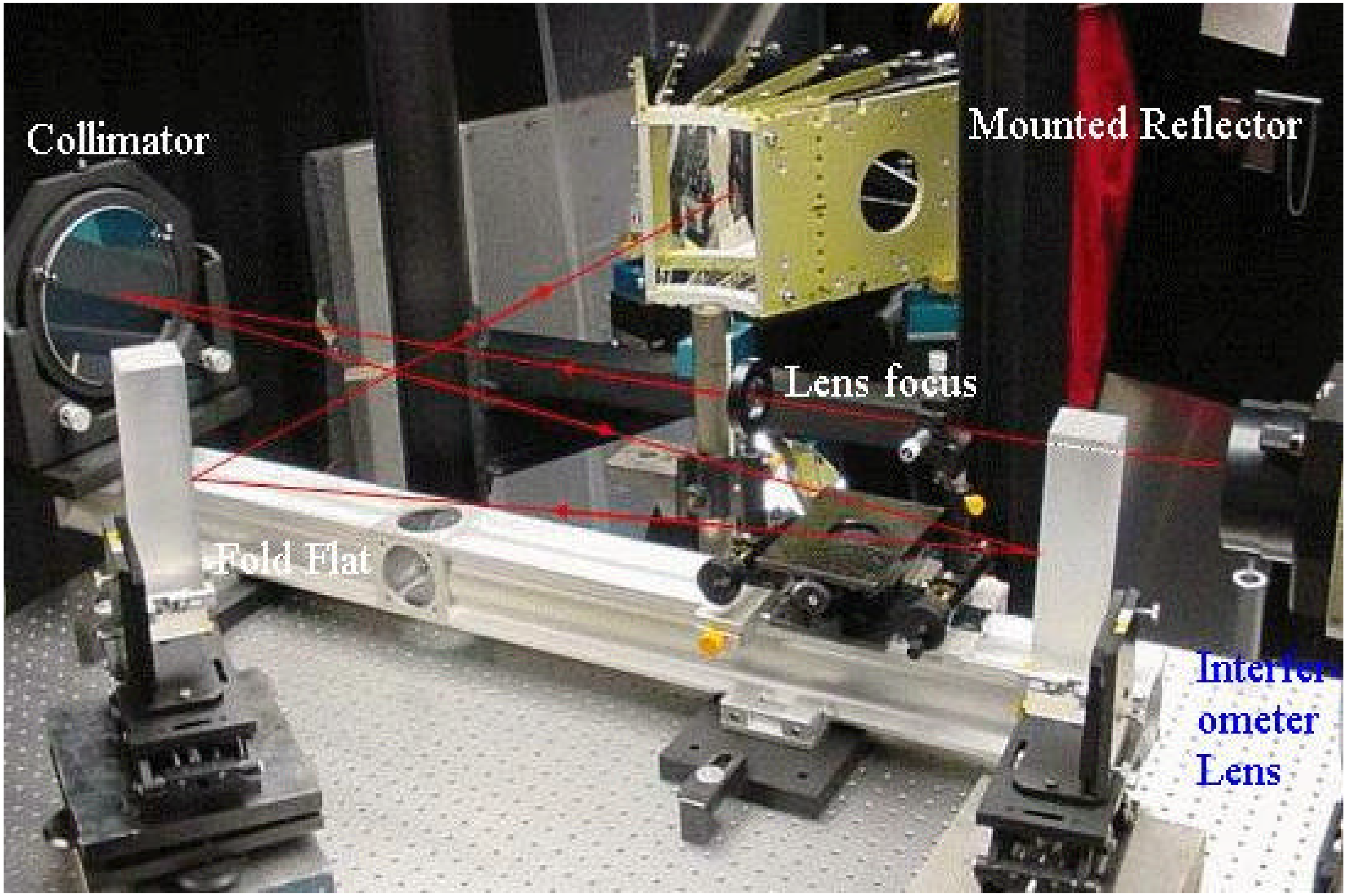


- Alignment scheme incorporates five independent positioners, top and bottom, plus two vertical positioners
- Interferometer viewing through window in hub provides feedback on figure distortions
- Centroid Detector Assembly (designed for Chandra mirrors) is used to determine focal point and reflector distortions





In-situ axial figure station

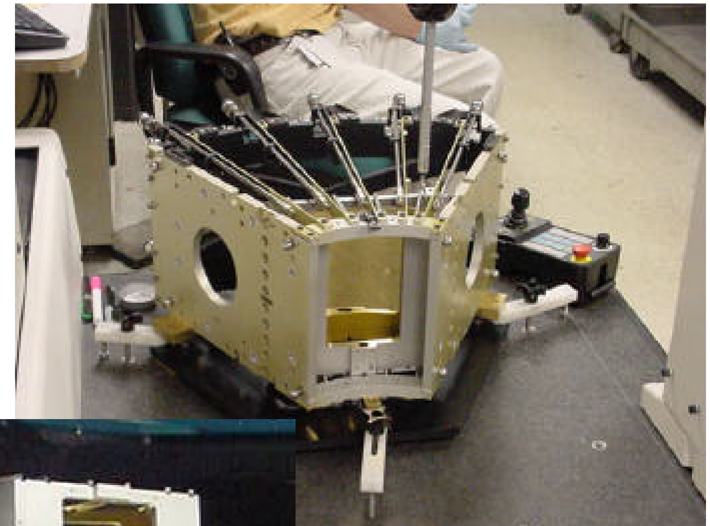


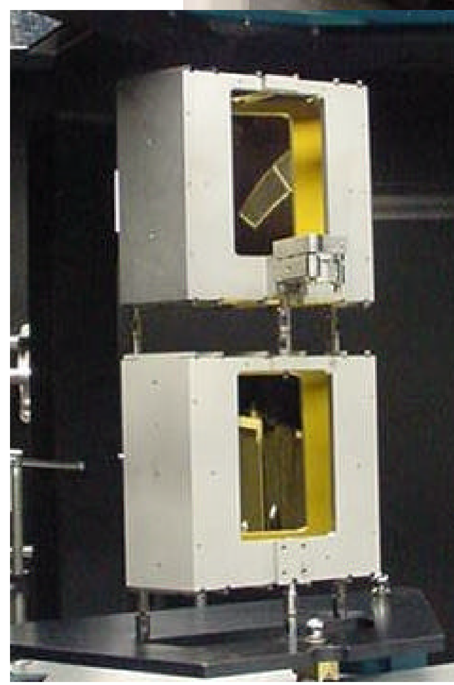
Summary of lessons learned with OAP-1

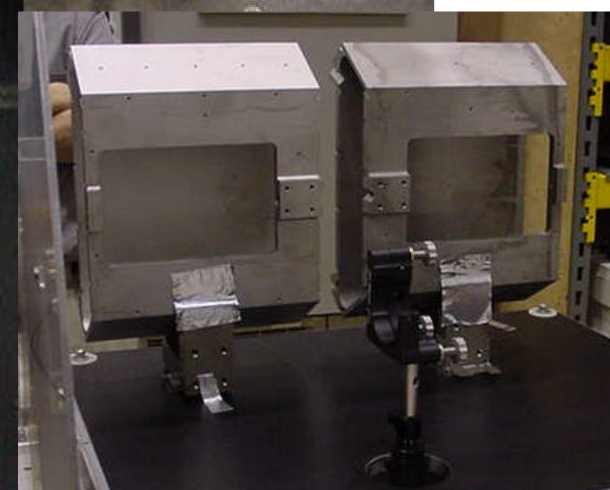
- Satisfactory alignment quality can be achieved with CDA and in-situ axial interferometry
- Small differential adjustments of actuator pairs changes local average slope, but not local axial figure
- Common mode adjustments change 2nd order axial figure, but not local slope
  - Axial sag changes at ~0.2 microns per micron of common mode adjustment.
  - An adjustment at one position will effect the sag at least as far as the neighboring sets of actuators
- Common mode adjustments of all OAP actuators simultaneously yield little change in axial figure

Optical Alignment Pathfinder 2

- Designed to work in tandem with the OAP1 unit
  - OAP2 is a monolithic titanium housing, EDM cut from a single parent block
  - Nests inside the OAP1 structure. Uses the precision alignment arms of OAP1
- Once alignment with OAP1 arms is done, and mirrors bonded, OAP2 units stack up, and are bonded together.
- Entire unit can then be turned horizontal for x-ray testing.
- Structure is very thick, minimizing gravity distortions to mirrors

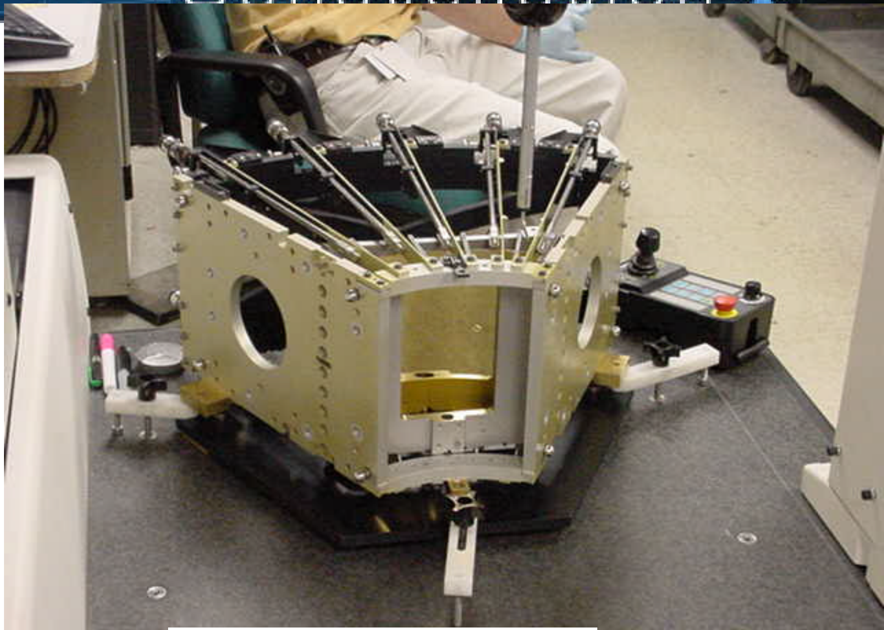




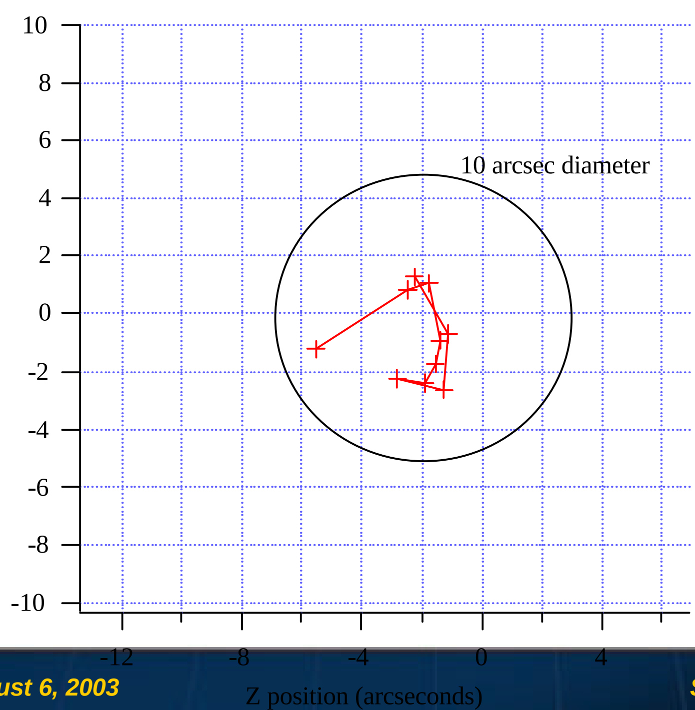


Mirror alignment in OAP2

- Bottom radial support arms are located using CMM and bonded on OAP2
- Mirror is place in housing and top radial support arms are located and bonded.
- OAP2 is inserted in OAP1, ruby ball fingers capture mirror, and are located using CMM
- OAP1/OAP2 unit is mounted in CDA tower, and actuators are fine adjusted to focus each return beam to a coincident point
- Initial mirror alignment yields good quality, but not quite flight requirement
  - 5.89” RSS of points from centroid vs 3.38” requirement
- Difficulties with secondary mirror figure has limited us so far from getting good alignment with a mirror pair.



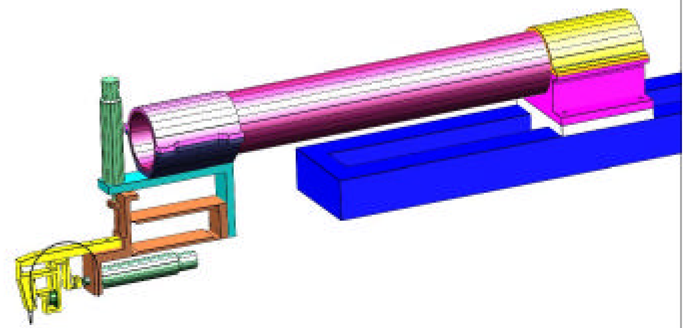
P mirror alignment w/CDA

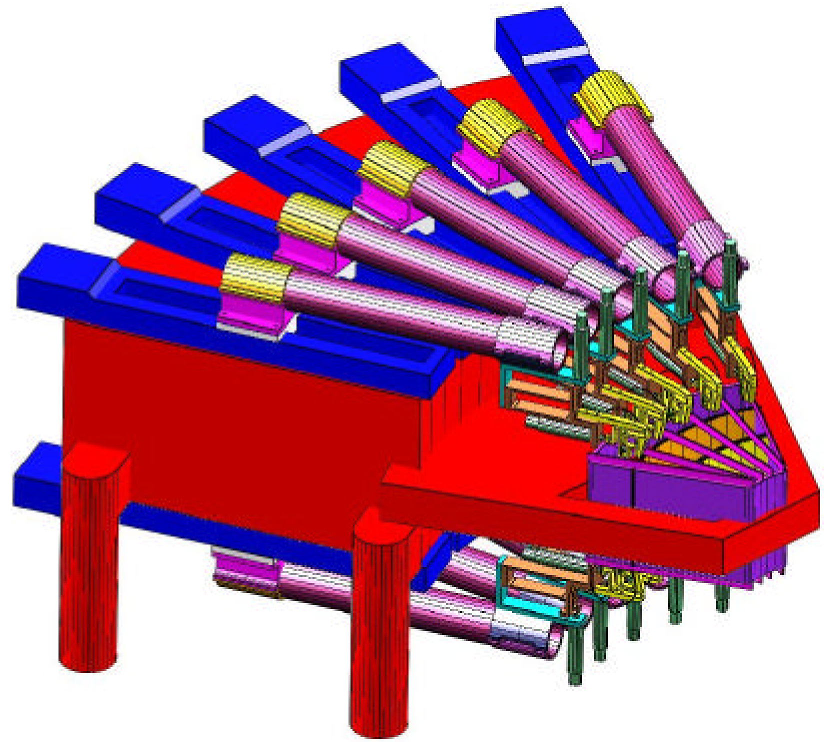


Tooling for Mass Alignment Pathfinder

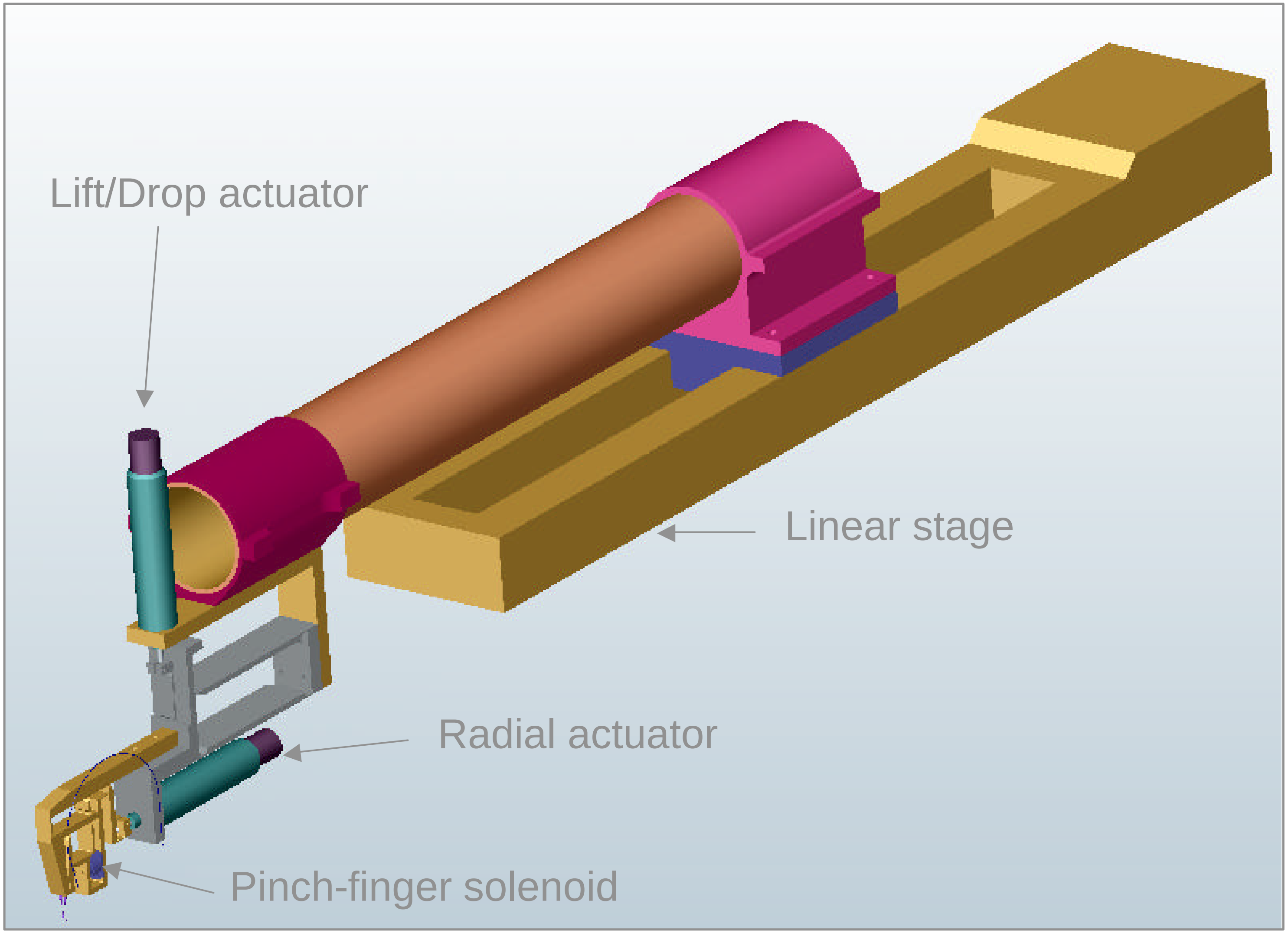
Mass Production Tooling:

- Intent to combine precision actuator output with CDA output in computer controlled loop
- Investigating this summer using a single manipulator arm
- In parallel, refining requirements on etched Si microstructures
- Automated alignment concepts will be incorporated into Engineering Unit





General arrangement of robotic arm



Automated alignment signal flow diagram

CDA shoots 1 point →

CDA determines slope error at particular point →

Error signal converted to error vector

Actuator Displacements = [Influence coefficient matrix] * {error vector)

Check limits

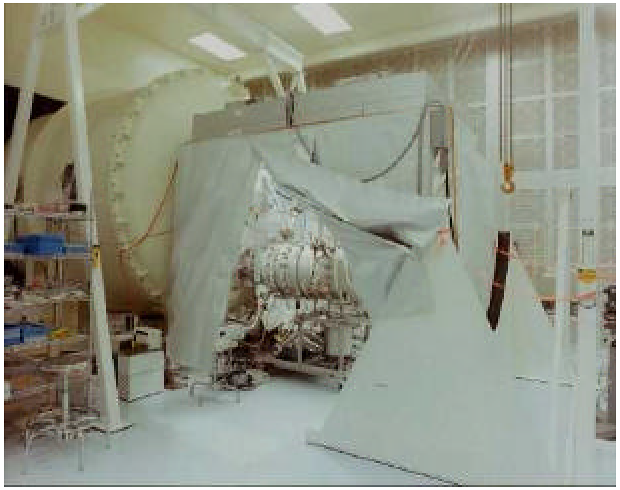
Move actuator command

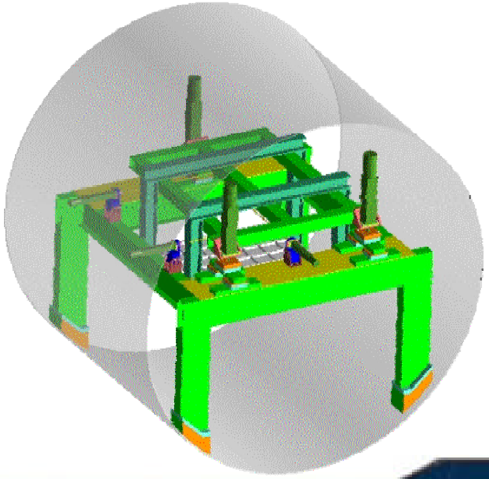
Actuators move

Mirror deforms

Preparation for X-ray Performance Testing

- **X-ray performance testing will be performed at MSFC 100-m Stray Light Facility**
- **Special, massive 6-degree of freedom optical table has been developed especially for SXT tests**
- **Performance test "dry run" will commence within ~ one month**
- **First performance test contingent upon production of reflectors that meet figure requirement**





Plans for Coming Year

- Continue improving 50 cm reflector substrate figure - key to success
  - Refinement of forming - more uniform temperature
  - Obtain forming mandrels with 2-4 arc second figure
  - Reduce epoxy thickness
- X-ray test of reflector pair (in OAP2 housing)
- Construct Engineering Unit
- Develop automated alignment scheme
- Incorporate CDA measurements into computer-controlled feedback loop for reflector alignment
- Establish facility for producing 1.6 m reflectors
  - Replication and coating chambers have been ordered
- Initiate industry studies of Flight Mirror Assembly (RFI released)
  - Anticipate two parallel design studies
  - Prelude to selecting FMA contractor in 2005

The SXT/FMA Technology Development Team

- Integrated team, with participants from several institutions
- Key activities and leads:
  - Technology development management (D. Nguyen, GSFC)
  - System engineering and mechanical modeling (B. Podgorsky, SAO*)
  - Optical design and modeling (T. Saha, GSFC*)
  - Reflector development (W. Zhang, GSFC*)
  - Alignment (S. Owens, GSFC*)
  - Metrology (D. Content, GSFC*)
  - Thermal design and modeling (M. Freeman, SAO)
  - Housings (J. Stewart, GSFC)
  - X-ray calibration (S. O'Dell, MSFC*)

*in attendance

Mass Alignment Hardware Block Diagram